Effects of Road Salt Applications on Human and Ecological Health: A Risk Assessment and Risk Management for Prospective Policy Options

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Executive Summary

Under many winter weather conditions, the use of de-icing chemicals is deemed necessary to maintain safe traveling conditions. Salt applications are used as the most effective method for treating ice and snow. Depending on the weather conditions, 10 to 20 million tons of de-icing salts are used in the United States each year. Although alternatives exist, the most commonly used material for de-icing is sodium chloride (NaCl). Chloride is extremely soluble in water and cannot be destroyed, only diluted; once applied to a road, it migrates easily through surface or ground water to tributaries, reservoirs, soils, and watersheds. Studies have shown that road salt leaches into the ground and changes soil composition, making it hard for plants to survive; damages vegetation and soils along the shoulders of roads, causing erosion; deteriorates buildings, bridges, and paved surfaces; clogs stormwater catch basins and streambeds, resulting in higher potential for flooding; and accumulates in drinking water reservoirs near highways and salt storage areas, where high levels of sodium contribute to cardiovascular, kidney, and liver diseases. These risks, along with countless others, cannot be mitigated without policy.

This analysis characterizes the risks to human and ecological health by using the risk assessment and risk management paradigm. Exposure assessment data shows that groundwater and drinking water sources observe salt concentrations above the limits set by the Environmental Protection Agency (EPA). Laboratory conducted dose-response analyses were drawn on to show the effects of road salt on ecological settings including terrestrial wildlife, aquatic life, and vegetation. Dose-response data shows varying responses of species to different dosages of the contaminant ranging from acute survival to lethal dose. A separate human health risk assessment showed

increased risks of car accidents and injury in addition to high economic costs if no deicer is used in dangerous weather conditions. The risk characterization illustrates all primary risks, pathways, and a wide range of secondary risks including invasive species, reduced biodiversity, reduction in recreational and market fishing, in addition to high economic costs resulting from primary and secondary risks. Policy options were developed that would mitigate risks by using less or no salt through human behavior changes, chemical alternatives, technological and mechanical applications, and research and development of new and existing methods. Policy options were analyzed based off of effectiveness at reducing risks, cost of implementation, technical feasibility, and degree of public acceptance. Not all possible policy options were found to be feasible. The use of alternative deicers and calibrated deicing equipment was shown to be effective and not cost inhibiting. Regional analyses to explore the effectiveness of policy options would result in the least data limitations and highest reduction of risks to human and ecological health.

I. Introduction

I. Research statement

The objective of this study is to examine the effects and risks of road salt on ecological and human health using the risk assessment and risk management paradigm as defined by the EPA so as to develop policy options to mitigate those risks. The pathway of the contaminant will be observed from source to receptor. The ecological health of both terrestrial and aquatic biota and human health will be evaluated. The economic impacts associated with the risks will be considered in developing policy options. Policy options will include human behavior changes, technological and mechanical applications, and research and development of methods that would result in the use of alternative deicers or less and/or no salt use policies.

II. Background

De-icing chemicals work by lowering the freezing point of water. The prevalent salt used in North America is NaCl, which is comprised of approximately 60% chloride and 40% sodium by weight. Other trace elements may include phosphorous, sulfur, nitrogen, copper, and zinc (Environmental Canada, 1991). Mined rock salts are the most common extraction of NaCl, which are crushed and screened to a mixture of three-eighths of an inch granules. In addition, the mixture is often treated with additives containing cyanide to prevent the salt from caking (Siegel, 2007).

Table 1 below outlines the key properties of NaCl, which influence its transport and characteristics and ultimately its potential exposure to human and ecological receptors. The eutectic temperature defines the lowest temperature at which the substance will melt, and the working temperature dictates the lowest effective de-icing temperature (Environmental Canada, 1991). The compound's high solubility allows it to be extremely mobile, while its high particle density allows the compound to sink to the bottom of waterbodies (Siegel, 2007). Henry's law constant and the vapor pressure of sodium chloride indicate that NaCl does not volatilize from water, air, or even moist soil surfaces. The compound may however associate with suspended particulate matter or water droplets (USEPA, 2003a).

Table 1: Properties of NaCl Road Salt	
CAS Number	7647-14-5
Molecular Weight	58.44 g/mol
Eutectic Temperature (℃)	-21
Working Temperature (℃)	0 to -15
Water Solubility (g/L)	357 at 0℃ - 25℃ 391.2 at 100℃
Melting Point	800.8℃
Color	White
Odor	Odorless
Specific Gravity	2.165
Density	> 1 ton per cubic yard
Vapor Pressure at 865 ℃	0.1 kPa (1 mm Hg)
Henry's Law Constant at 20 ℃	K= 1211 Pa, $1/H = 4.3 \times 10^5$

(Environmental Canada, 1991) (Siegel, 2007)

Climate, road salt loading, surface and subsurface soil conditions, and location of the site within the overall hydrogeological environment are all primary factors that determine the degree to which road salts may impact biota. Melting ice or snow requires heat from external sources such as the sun, air, pavement, or traffic friction. Salt may be able to migrate via air currents, facilitated by traffic motion in places where there is insufficient moisture for salt to dissolve. Alternatively, the solid salt may spread by accumulating on nearby vegetation in areas of high salting or if ingested by local wildlife (Siegel, 2007).

The principal concern regarding road salt is its high solubility in water. Overland flow can occur when road salt migrates across impervious surfaces such as roadways and parking lots. This flow migrates to surface waters such as streams, wetlands, and lakes. Some precipitation with dissociated salt ions will percolate through shallow soils, moving downward into the vadose zone and eventually into the water table (Environmental Canada, 1991).

Chloride mainly circulates through the hydrological cycle by physical processes. The chloride ions pass readily through soil, enter groundwater, and eventually drain into surface waters (TRB, 1991; Siegel, 2007). Chloride ions cannot be destroyed, only diluted, and as such are trapped in the hydrological cycle. Due to the persistence of chloride, all chloride ions applied to roadways as road salts will eventually reach surface waters (Environmental Canada, 1991).

Dilution of road salt can occur with increased rates of recharge to groundwater. Typical concentrations of chloride in water depend on the type of water, with freshwater lakes averaging 0 to 100 mg/L and seawater averaging approximately 20,000 mg/L (Siegel, 2007). In the past twenty years however, chloride concentrations greater than 10,000 mg/L have been reported in freshwater following nearby road salt applications; such extremes are often observed near large roadside snowbanks (TRB, 2001).

Sodium chloride can alter the biogeochemistry of surface waters via two primary mechanisms. Sulfate (SO_4^-) concentrations in surface waters have declined since the 1980s following the introduction of cleansing technologies and a switch to cleaner fuels, thus NaCl has provided an alternative mobile anion (Cl^-), thereby influencing soil base cation leaching. The second mechanism includes the process by which sodium migrates through the soil and exchanges with other cations; these exchanged ions become mobile and migrate through groundwaters to surface waters, increasing the cation concentration in these waters (Rosfjord *et al*., 2007). The acid neutralizing capacity of a water body depends on the sum of the major base cations. With chloride acting as a mobile anion, which can leach and exchange cations, the ability of a surface water to buffer acid deposition is reduced. The acidity of a water body can affect organisms living in the water, release toxic compounds such as aluminum, introduce invasive species, and cause eutrophication (Siegel, 2007).

Sodium infiltration can change the chemical composition of soil. Soil naturally possesses a negative charge and requires a positive charge to balance it, usually supplied by calcium and magnesium. Sodium is less preferable than these other two elements because sodium has a comparatively lower positive charge to balance out the net charge. When sodium is introduced to soil in large volumes, it tends to override other nutrients and deprive the soil of valuable minerals. Sodium also causes clay to become impermeable through the same means of sudden over nutrification (Rosfjord *et al*., 2007).

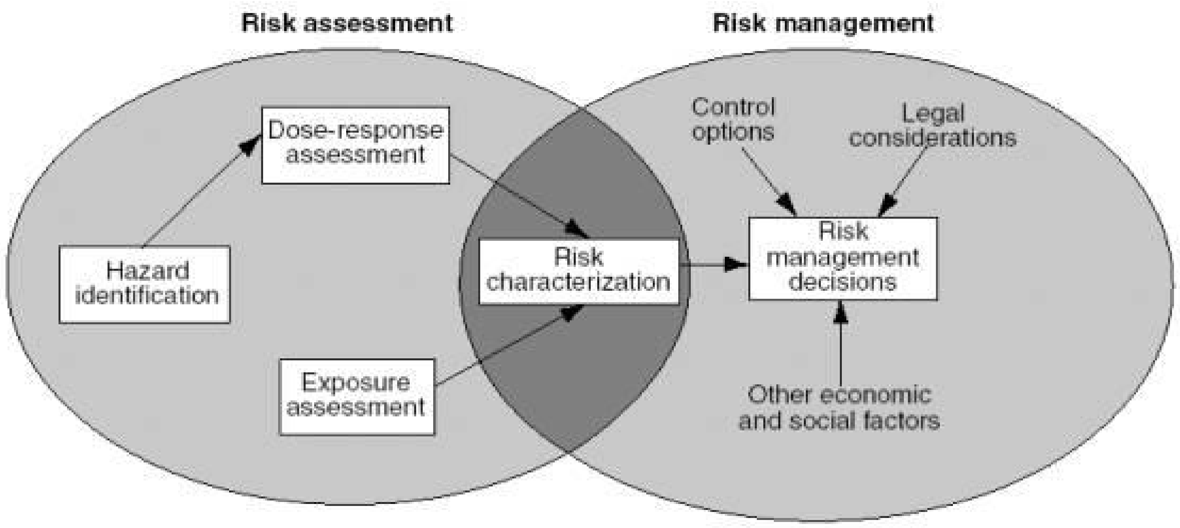
Salts in soil may inhibit plant growth in two ways. The presence of salt in the soil reduces the plant's ability to take up water, leading to reductions in the growth rate referred to as the osmotic or water-deficit effect of salinity. When salt accumulation occurs on vegetation, excessive amounts of salt enter the plants transpiration stream and injury to the cells occur in the transpiring leaves, which may cause further reductions in growth (Montoliu *et al*., 2009).

Though anti-caking agents are not typically found in the crystalline salts that homeowners can purchase to use on sidewalks, they are found in road salts. These anti-caking agents contain cyanide, without which salt crystals would congeal into chunks that are impossible to spread on roadways. Certain bacteria break down the additives in road salt, releasing free cyanide into the environment. The additives can also photodegrade in sunlight, thereby releasing cyanide (Siegel, 2007). Cases of pet poisoning in winter have increased as cats and dogs trap the road salt in the pads of their paws and lick off the toxic substance, which can cause severe seizures, comas, or even death. Currently, there are no federal or state laws mandating how much road salt can be used or optimizing road salt usage.

II. Methods

To estimate potential health impacts associated with environmental exposures, Environmental Protection Agency (EPA) scientists, regulators, and others have spent more than two decades developing an extensive set of risk assessment methods, tools, and data to estimate environmental health risks. Although uncertainties remain, the risk assessment and risk management methodology has been extensively peer-reviewed, is widely used and understood by the scientific community, and continues to expand and evolve as scientific knowledge advances (USEPA, 2014). The EPA's framework for assessing and managing risks reflects the risk assessment and risk management paradigm set forth by the National Academy of Sciences (NRC) in 1983, shown in Figure 1 below. The 1983 NRC report identified four steps integral to any risk assessment: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment and (4) risk characterization. This analysis will draw on the risk assessment paradigm to identify and characterize the risks associated with road salt and its effects on human and ecological health. The second part of this analysis will include prospective management options using tools outlined by the risk management paradigm, such as research and development of technologies, alternatives, policies, and regulation.

Figure 1: Risk Assessment and Risk Management Paradigm



Source: EPA Office of Research and Development.

Typically, there are three phases to a risk assessment. First is problem formulation; the problem is defined, and a plan for analyzing and characterizing the risks is determined. For this report, the initial work in the problem formulation included integration of available information on sources, stressors, effects, and ecosystem and receptor characteristics. Road salt was characterized by drawing on academic sources to explain its chemical make-up, the pathways it follows due to its physical and chemical properties, and the main ecological receptors which were found to be drinking water, wildlife, aquatic life, vegetation, and soil. The second phase is analysis, where data are evaluated to determine how exposure to stressors is likely to occur and, given this exposure, the potential and type of ecological effects that may be expected. The analysis phase was conducted by using dose-response analysis from academic and institutional studies examining specific species response to the stressor in addition to more broad taxonomic responses to the stressor. The problem formulation identified drinking water, wildlife, aquatic life, vegetation, and soil as the main end receptors of the source, and as such, dose-response assessments were used that identified the effects road salt has on those end receptors. The third phase is risk characterization, where exposure rates and stressor-response profiles were integrated through the risk estimation process using a conceptual model. The conceptual model expanded on the data from the problem formulation and the analysis phase to show primary pathways of the stressor, resulting risks, primary risks, and economic affects. Apart from the conceptual model, included in the risk characterization is a summary of assumptions, scientific uncertainties, and strengths and limitations of the analyses.

Road salt is a unique risk factor, in that its absence can also inherently jeopardize human health. To fully characterize this additional risk, another risk assessment was performed to analyze the human health risks associated with a lack of road salt. This risk assessment will not utilize all the same tools as an ecological risk assessment because no source, dose-response, stressors, or pathways will be observed. Data from state departments of transportation were used to characterize the risks to human health regarding car accidents and slipping incidents in dangerous weather conditions. Another conceptual model was prepared to illustrate the risks associated with no de-icing.

Risk management is a public policy decision making process, and as such, it typically involves competing interests and thus an array of goals and approaches. Risk assessments are designed to provide information to risk managers about the potential adverse effects of different management decisions. Eliminating risks associated with human activities can present challenges to risk managers due to unpredictable variables and potentially high costs. Management options may range from preventing the introduction of a stressor to restoration of affected ecological health to providing costly treatments for human health damages.

Risk management typically begins with the choice of a risk management goal, in this case determined in our risk assessment. There are often many goals to consider based on the nature of the problem being addressed, the competing societal interests at stake, and the analytical methods used to inform decision making. Risk management goals can include the introduction or modification of common law, insurance, voluntary standard setting, individual and corporate initiatives, mandatory government standards and regulations, and market-based solutions (USEPA, 1998). For this report, risk management goals were chosen that would prevent the stressor from following it pathway outlined in the risk characterization, and thus ultimately breaking the cause-effect link and mitigating the risks to human health, ecological health, property, and economic factors.

Options matrix, also referred to as options theory, is a tool often used during risk management analysis to introduce logical and systematic approaches for developing solutions to address an environmental risk. The approach begins by developing a simple box and arrow diagram that explains the cause-effect relationships that result in the environmental risk. Between each cause and effect box is a possible point of intervention. These points of intervention are actions that break the cause-effect link and thereby mitigate the ultimate effects identified. A literature search was undertaken to discover what points of intervention would necessitate in order to break the cause-effect link. Points of intervention for the risk management were analyzed with the following considerations: technological innovations, federal and state policy, alternative compounds, voluntary approaches, social changes, and education. Each point of intervention was further analyzed to find methods, technologies, chemical compounds, and even changes to human behavior that could mitigate the risks. The risk management paradigm typically includes a set of criteria to evaluate the effectiveness of the points of interventions. These criteria include, but are not limited to, effectiveness, feasibility, economic impacts, adaptability, cost-effectiveness, and equity (Koines, 2017). Figure 2 is a simple template often used in many risk management analyses to measure the level of risk by considering the consequence/severity and likelihood of injury. In this project, the matrix outlines the points of intervention that were identified and their likelihood to be efficient using the parameters discussed above, as opposed to risks and consequences like the example matrix below.

Figure 2: Options Matrix Template used in Risk Management Analysis

Likelihood		Very Likely	Likely	Unlikely	Highly Unlikely
Consequences	Fatality	High	High	High	Medium
	Major Injuries	High	High	Medium	Medium
	Minor Injuries	High	Medium	Medium	Low
	Negligible Injuries	Medium	Medium	Low	Low

III. Results

This results section is comprised of 5 subsections. First we will observe human physiological health risks associated with road salt usage in ground and drinking waters. Next, risks to ecological health will be examined through the use of dose-response analysis. Ecological health will be analyzed through three separate ecological communities: terrestrial wildlife, aquatic life, and vegetation. As mentioned previously, the absence of road salt, with no alternatives to replace it, results in its own human health risk. Section three observes the risks to human life if road salt is not used in dangerous weather conditions. This analysis will draw on state highway car accident occurrences in addition to secondary economic impacts. When examining a human and ecological health risk that is so vast in geographic scope and follows countless pathways, there will be many data limitations. Section four discusses the data limitations, mainly that uniformity cannot be expected throughout the scope of this analysis; to minimize data limitations, the analysis would have to be conducted on a regional scale. The last part of the results section will full characterize all the risks to human and ecological health, following the pathway of the stressor and presenting secondary risks in addition to economic affects.

I. Risk Assessment: Human Health Impacts of NaCl

Table 2 shows the first maximum contaminant level for sodium that was set by the EPA for organoleptic purposes; at 250 mg/L, sodium compromised the taste of water. Now there is a new monitoring limit required by the EPA setting an advisory drinking water limit of 20 mg/L of NaCl for public water systems, where any higher concentration must be reported to local health authorities (USEPA, 2003a). The EPA set this limit to combat hypertension (high blood pressure greater than 140/90; Siegel, 2007). Hypertension, if left untreated, can lead to cardiac disease, renal disease, hardening of the arteries, eye damage, and stroke. Approximately 20% of adults in the United States have hypertension (Cunha, 2004).

Table 2: Sodium and Chloride Toxicity to Human Health

Contaminant	Threshold (mg/L)	Test Reference
Chloride	250	EPA Secondary Drinking Water Standard (for taste)

Contaminant	Threshold (mg/L)	Test Reference
Sodium	20	EPA advisory limit for drinking water
	250	EPA secondary maximum contaminant level

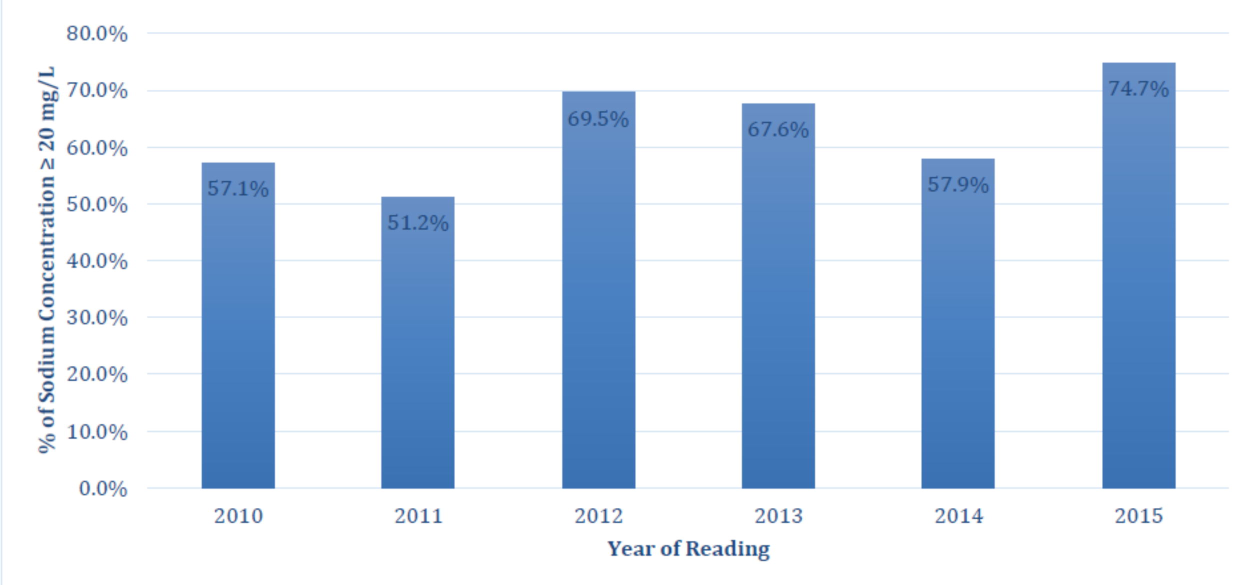
(USEPA, 2003a)

The human body must maintain homeostasis, in which somatic cells balance water intake against water losses from renal excretion, respiratory, skin, and gastrointestinal sources. Each of these processes is controlled by sodium-controlled channels. When there is excess sodium in the body, cells become dehydrated due to the osmotic pressure of the excess extracellular sodium extracting water from the cells; dehydrated cells attempt to counteract the shrinking of the cell structure by transporting electrolytes across the cell membrane (Siegel, 2007). After, cells attempt to restore cell volume and prevent structural damage by generating organic solutes within the cell. Severe cell shrinkage and stretching may damage the central nervous system by causing intracranial hemorrhages or cerebral edema. Such damage to the central nervous system can further lead to convulsions, confusion, and comas (Semenovskaya, 2018; USEPA, 2003a). Although most salt intake in humans is sourced from salt in foods, acute salt toxicity that would result in the damage to the central nervous system is only observed in ingestion through liquid mediums.

Damages to roadside vegetation can also intensify the impacts on drinking water quality by limiting the retention and processing of pollutants transported in run-off, in addition to diminishing the buffer zones to groundwater sources and reservoirs.

Figure 2 shows a study conducted by the Worcester Polytechnic Institute, which found that the majority of groundwater sources in Massachusetts currently have sodium concentrations above the EPA recommendation of 20 mg/L. They also found that the sodium concentrations of groundwater wells in Massachusetts had been increasing. The study included interviews with water suppliers. All three water suppliers that were interviewed agreed that sodium was not the most concerning pollutant in their systems. This lack of concern is likely because there is no enforceable limit on sodium concentrations, and other pollutants such as volatile organic compounds are more predominant and injurious. Additionally, the water suppliers stated that customers rarely call in to complain about sodium concentrations, as they are preoccupied with other, more visible pollutants, such as manganese and chlorine (Gigliotti *et al*., 2015).

Figure 3: Percentage of Groundwater Sources in Massachusetts with an Average Sodium Concentration ≥ 20 mg/L by Year



(Gigliotti *et al.*, 2015)

II. Risk Assessment: Ecological Health Impacts of NaCl

EPA guidelines on exposure and toxicity potentials of NaCl road salt on ecological health provide that acute toxicity occurs when a dose or concentration causes an effect in 50% of the tested population. Laboratory toxicity studies using standard test organisms were used to determine the toxicity endpoints. Dose-response analysis from academic and federal studies were drawn on to observe salt toxicity on terrestrial wildlife, aquatic life, and vegetation.

A. Terrestrial Wildlife

Road salt may affect wildlife through a variety of pathways. Animals may mistake the salt crystals for food; birds have been observed to mistake road salt for seeds. Wildlife may also ingest NaCl accumulated on foliage and dissolved in water. In areas of heavy salting, high concentrations of sodium and chloride can be found in snow melt, which many animals rely on to relieve thirst (Siegel, 2007).

Similar symptoms to those listed for humans occur in wildlife when salt homeostasis fails. Mammals can remove the excess sodium by increasing the filtration rate of the kidneys and decreasing the percentage of sodium that the kidneys reabsorb (Mineau and Brownlee, 2005). However, the renal system of some organisms, such as birds, are not capable of doing this.

The impacts of chloride alone on wildlife are not as uniform throughout organisms. The concentration of NaCl in water, below which is considered safe for wildlife is 1,000 mg NaCl/L, compared to 600 mg Cl^-/L (Nagpal et al., 2003). Many laboratory-conducted studies examine the effects of NaCl on single species at different dosages and concentrations. For a small-scale regional approach to this issue, such information would be critical to understand which species are at the greatest risk. While examples of dose-response data will be included in this assessment, it is important to note that it is not feasible to conduct these experiments for every species included in the geographic scope, nor is it necessary for successful policy. The aim is to show that a large enough range of species are affected, so assumptions can be made that there is an overall negative effect.

A study by Mineau and Brownlee analyzed the conditional toxicological value (CTV) concentrations above which certain effects were expected. The results showed homeostasis failure and edema of gizzard at concentrations below the limit set by EPA considered safe for wildlife. Also examined in this study was the use of various sized salt crystals to grasp the relative risk of salt that has not yet dissolved into a brine solution, shown in Table 3.

Table 3: Sodium CTV and Number of Salt Particles for Impacts

Critical Toxicological Value (mg/Na^+ / Kg body weight)	Effect	Number of Salt Particles	
		0.5 mm diameter particles	2.4 mm diameter particles
266	Homeostasis failure	52	0.47
500	Edema of gizzard	98	0.88
1500	Overt signs of toxicity	294	2.6
3000	Lethal dose	587	5.2

(Mineau and Brownlee, 2005)

B. Aquatic life

The aquatic species typically considered in assessments of water quality are fish, macroinvertebrates, insects, and amphibians. Aquatic organisms require chloride to maintain normal physiological functions but only at relatively steady concentrations to which the organism has adapted. When exposed to excess or highly fluctuating chloride levels, aquatic organisms' abilities to survive, grow, and reproduce are put at risk (Siegel, 2007).

Aquatic species vary immensely in their ability to tolerate NaCl. Depending on whether fish are fresh or salt water species, they can tolerate between 400 and 30,000 mg/L. As road salting occurs, salinity increases overtime, resulting in changes to ecological community structures, towards more adaptive and salt tolerant species. increased abundance of salt tolerant species and. Certain aquatic species may adapt to increased levels of chloride with time; surviving organisms may develop the ability to handle the osmotic stress imposed by excess chloride. Saltwater aquatic species are not typically vulnerable to anthropogenic sources of NaCl, such as road salt, except for fluctuations greater than 10% (Environmental Canada, 1991).

Table 4 shows the results of a study conducted by the EPA that assessed the risk for various species by comparing toxicity thresholds and differing concentrations of NaCl. The thresholds did not include some key characteristics such as dissolved content, water hardness, alkalinity, density, or pH.

Table 4: NaCl and Chloride Toxicity Thresholds for Aquatic Organisms

Species	NaCl (mg/L)	Cl(mg/L)	Response Time	Response
American eel	17,964 – 21,571	10,900-13,085	4 days	Acute survival
Bluegill	14,100	8553	1 day	Acute survival
	9,627-12,964	5,840-7,864	4 days	Acute survival
	20,000	12,132	6 hours	Acute survival
Caddisfly	5,526-7,014	4,039-4,255	4 days	Acute Survival
Chironomid	5,192-6,637	3,795-4,026	4 days	Acute Survival
	9,995	6,063	12 hours	Acute Survival
Cladoceron	2,724-7,754	1,652-4,704	1 day	Acute Survival
	2,308-6,709	1,400-4,071	4 days	Acute Survival
	2,077-6,031	1,261-3,660	7-10 days	Sub-chronic survival
	1,225-5,777	735-3,506	7-10 days	Sub-chronic reproduction
	4,310	2,616	7-10 days	Sub-chronic weight

Species	NaCl (mg/L)	Cl(mg/L)	Response Time	Response
	518	314	21 days	Chronic
	727	441	21 days	Chronic
Diatom	2,430	1,474	7-10 days	Sub-chronic cell numbers
Fathead minnow early life stage	7,650-10,831	4,600-6,750	4 days	Acute survival
	2133	1,280	7 days	Sub-chronic
	415	252	33 days	Chronic
	580-722	352-433	33 days	Chronic
Fathead minnow embryo	1440	874	7-10 days	Sub-chronic survival
Fathead minnow larvae	4,990	3,029	7-10 days	Sub-chronic growth
	5,490	3,330	7-10 days	Sub-chronic survival
Frog	2,540	1,524	7-10 days	Sub-chronic survival
Goldfish	7,341	4,453	4 days	Acute survival
Isopod	4,896	2,970	4 days	Acute survival
	4,896	2,970	4 days	Acute survival
Rainbow trout	11,112	6,743	4 days	Acute survival
	20,000	12,312	6 hours	Acute survival
Snail	4,088	2,480	4 days	Acute survival

(Environmental Canada, 1991; USEPA, 1988)

The results show that freshwater species react differently to various exposures, with effects ranging from acute to lethal to sub-chronic and chronic responses. Invertebrate species are generally more sensitive to chloride than vertebrate species.

In 1998, the EPA released a Chloride Guidance Document, which set the final acute value for chloride as 1720 mg/L. The EPA set this limit after first identifying an acute criterion of 860 mg Cl^-/L and multiplying by a safety factor of 2. Based on this mean acute value, not all organisms are protected as seen in the dose-response analysis from Table 4. The final chronic value of 230 mg/L was derived by dividing the final acute value by the acute to chronic ratio of 7.593 (Siegel, 2007). The EPA states that these criteria only apply when the chloride is associated with sodium. Chloride toxicity increases when it is associated with other cations, such as potassium or magnesium, which may occur once the ions of road salt have dissolved and migrated.

A study performed by the Minnesota Pollution Control Agency (MPCA) showed that cyanide in the anti-caking agent interferes with a fish's ability to breathe and is thus lethal. In their study, toxicity levels of cyanide were identified for 30 fish species. They found that run-off from salt piles contained between 5 and 40 times the amount of cyanide that is toxic to half of the fish exposed in the study. The anti-caking agent sprayed on the road is diluted and is therefore not the primary concern; rather, it is the concentrated runoff from improperly managed salt piles (MSM, 2000).

As is common with many pollutants, water chemistry variables such as dissolved oxygen, temperature, and other contaminant concentrations affect chloride's overall impact. The presence of chloride can also increase or decrease the toxicity of other contaminants.

C. Vegetation

NaCl is considered an herbicide for many plant species. Physical symptoms of salt damage in vegetation include leaf scorch, late summer coloration, early fall defoliation, reduced shoot growth, twig and branch loss, and in extreme cases, death of the plant. Thresholds for sodium and chloride vary from species to species in addition to other variables such as temperature, light, humidity, wind, precipitation, water availability, salt exposure, plant size, and soil texture and drainage. High levels of salinity in soils decrease moisture retention and make conditions favorable for delay of water uptake by plants, which compromises both plant growth and soil erosion control (Siegel, 2007; Environmental Canada, 1991).

A study conducted by the New Hampshire Department of Environmental Services showed that in a particularly high-volume snow year, 14,000 trees along 3,700 miles of salt-treated highways died and had to be removed. Although not evaluated in this study, the impact of habitat loss would likely be exasperated by the many animals who relied on the trees for food and safety. Elevated levels of NaCl in soils of terrestrial, emergent aquatic, and submerged aquatic plants may generate an osmotic imbalance, which can obstruct the uptake of nutrients and inhibit the plant's long-term growth. Most vegetation damage occurs within 60 feet of the road with the worst damage taking place closest to the pavement, but impacts have been observed up to 200 meters from treated roads as NaCl migrates through water (Siegel, 2007).

Precipitation may alleviate some of the dehydration effects of NaCl by flushing salt deposits from foliage and diluting concentrations in water; however, it may also cause surface runoff of salt to roadsides, groundwater, and surface water (Mineau and Brownlee, 2005). Increases in temperature result in increased uptake rates of waters containing NaCl. Increases in temperature, light, and wind all compound the dehydration impacts of NaCl on plants by increasing evapotranspiration through foliage. Conversely, an increase in humidity decreases evapotranspiration and can alleviate salt stress.

A study was performed by Environmental Canada to observe the effects of varying degrees of sodium and chloride on terrestrial and aquatic plant species. In Table 5, effective concentration (EC) values refer to the concentration of a toxicant that induces a response between the baseline and maximum after a specified exposure time. EC50 induces a response halfway between the baseline and maximum; EC25 induces a response 25% of the way between the baseline and maximum. EC25 and CTV threshold values were estimated using scientific literature for chloride, sodium, and sodium chloride in growing media (soil, soil water, or water). Lowest-Observed-Effect-Level (LOEL) and No-Observed-Effect-Level (NOEL) threshold values were identified for sodium chloride and chloride in growing media.

Table 5: Toxicity Thresholds of Vegetation

Pathway	Plant Type	Form	Threshold	Units	Response type
Soil	Woody	Na^+	67.5-300	Mg/Kg soil	EC25
		Cl^-	215-500		EC25
		NaCl	600-1500		EC25

Pathway	Plant Type	Form	Threshold	Units	Response type
	Herbaceous	Na^+	202-270		EC25
Root uptake	All Species	Na^+	67.5-300	Mg/Kg soil	EC25
		Cl^-	215-500		EC25, LOEL
		NaCl	280-66,000		EC25, CTV, NOEL, LOEL
Solution	Wetland	Cl^-	300-1,500	Mg/L solution	LOEL
		NaCl	280-66,600		NOEL,LOEL
	Woody	NaCl	836-25,000		EC25, CTV
	Herbaceous	NaCl	<2,500-10,000		EC25
Surface water	Algae	Cl^-	71-36,400	Mg/L	Inhibition of growth and/or chlorophyll
	Desmid	Cl^-	200-250		Growth inhibition
	Diatom	Cl^-	642		EC50
	Eurasian milfoil	Cl^-	3,617-4,964		50% reduction in dry weight
	Angiosperm: seeds, 9week old plants, and 13-week old plants	Cl^-	1820		Reduced germination, dry weight, and shoots

(EC, 2001; USEPA, 1988; Siegel, 2007)

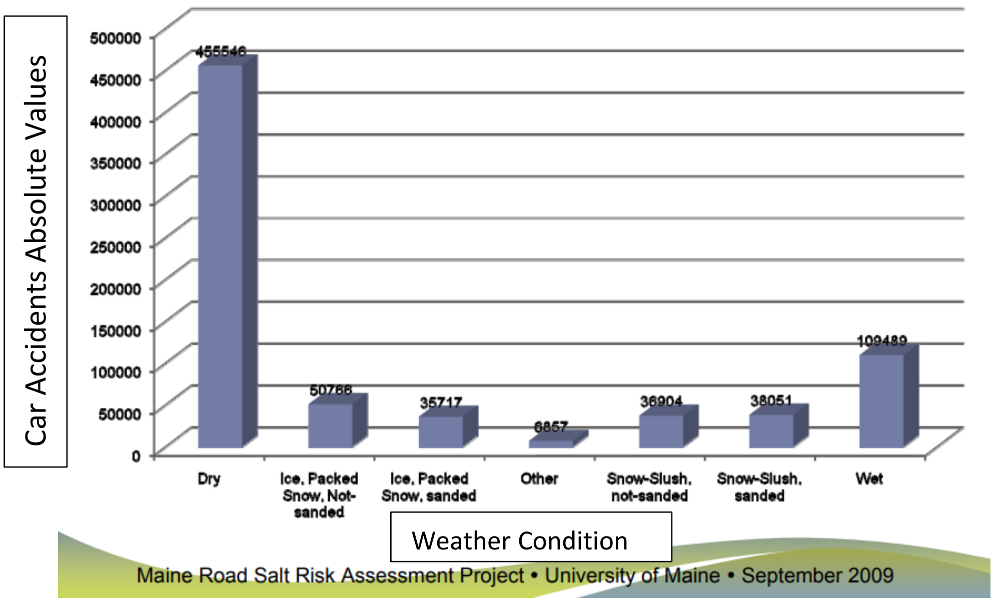
One algal species demonstrated high sensitivity to chloride exposure with concentrations as little as 71 mg Cl^-/L impeding growth and chlorophyll production, while other species could tolerate chloride concentrations between 886 mg/L and 36,400 mg/L. Aquatic plants exhibited various reactions. Growth inhibition was observed in desmids at 200 mg Cl^-/L, EC50 (1482 mg Cl^-/L) in diatoms, and reduced growth and reproduction at 1820 mg Cl^-/L in angiosperm (USEPA, 1988).

The results showed that both terrestrial and aquatic plant species are vulnerable to varying degrees of NaCl contamination. Cellular dehydration is primarily responsible for toxic effects observed in the plants.

III. Risk Assessment: Human Health Risks Using No Road Salt

One study from the Maine Department of Transportation and the University of Maine looked at the state's car accidents from 1989-2008 during different weather conditions. Figure 3 showed that "dry conditions", those conditions where no rain, snow, ice, or sleet was present, resulted in more car accidents than all other conditions combined (UoM, 2009). It is worth noting that the results did not show frequency that the accidents occurred in the given weather conditions, but rather absolute number of accidents over the 19 years analyzed. Although not explicitly analyzed in the study, there was an estimation that dry conditions are overall more frequent than the other weather conditions. The study thus does not prove that wet weather conditions are any safer, but rather shows that there is no evidence that less car accidents would occur in the absence of snow, ice, rain, or sleet.

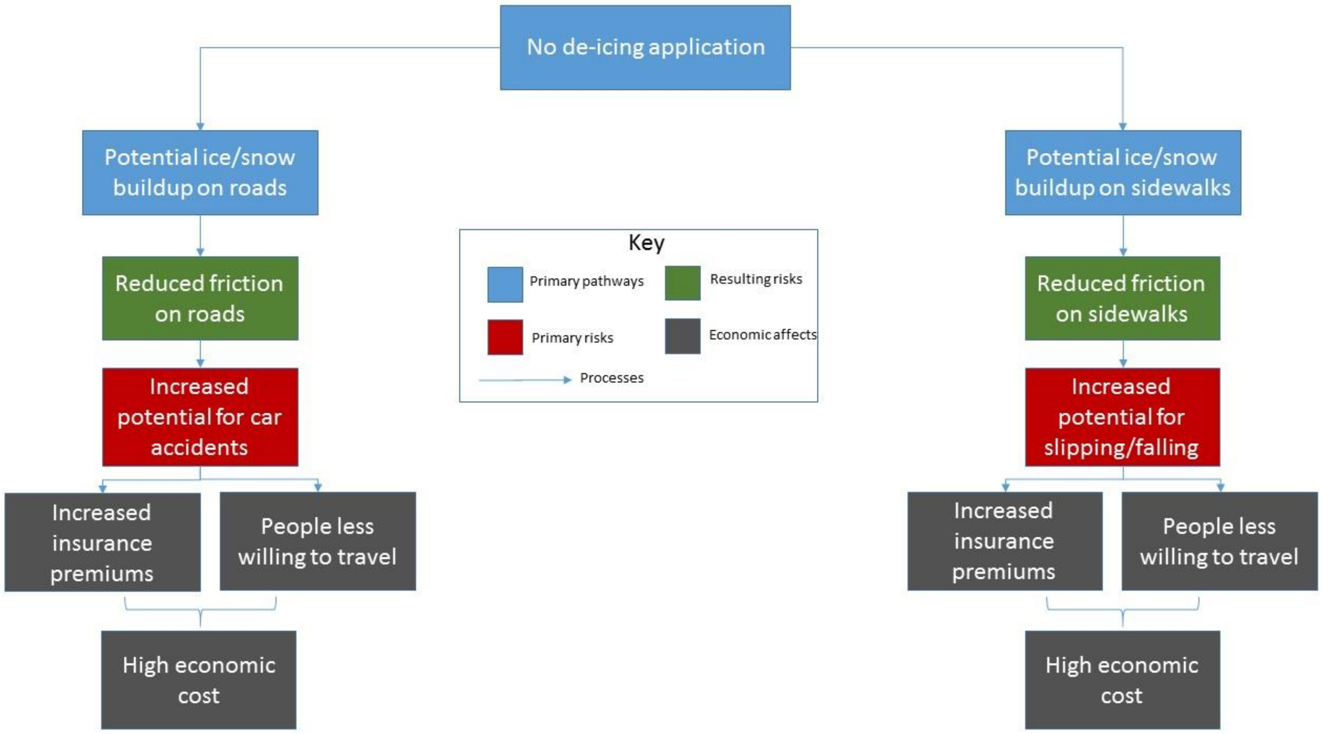
Figure 4: Maine Department of Transportation Crashes by Road Surface Condition 1989-2008



The Federal Highway Administration states that more than 1,300 people are killed, and more than 116,800 people are injured in vehicle crashes on snowy, slushy, or icy pavements each year. In a separate report they showed that in the same year there were 5,419,000 crashes total, with 30,296 fatalities. It is impossible to show if using road salts does actually have an effect on the number of car accidents and fatalities because there are so many variables involved. The population size, the type of car, tires, salt, snow, driving behavior, infrastructure, and so much more are all equally important in avoiding winter related car accidents.

To fully understand the risks associated with road salt, it is also necessary to understand the risks in a situation where no salt or de-icing method is used. Figure 4 shows a risk characterization of risks associated when no de-icing methods are applied.

Figure 5: Risk Characterization Conceptual Model for No De-icing Applications



The National Highway Traffic Safety Administration (NHTSA) lists speeding, and not weather related conditions, as the main cause of car accidents.

IV. Data Limitations

Many risk assessment analysis techniques involve gathering data. For example, developing models or simulations can help predict the impact of events, such as natural disasters caused by severe weather conditions or using state-level studies to analyze larger geographic trends. Unfortunately, many environmental risk assessments have data gaps due to the nature of environmental hazards, primarily as a result of a lack of understanding of the interconnected nature of ecosystems.

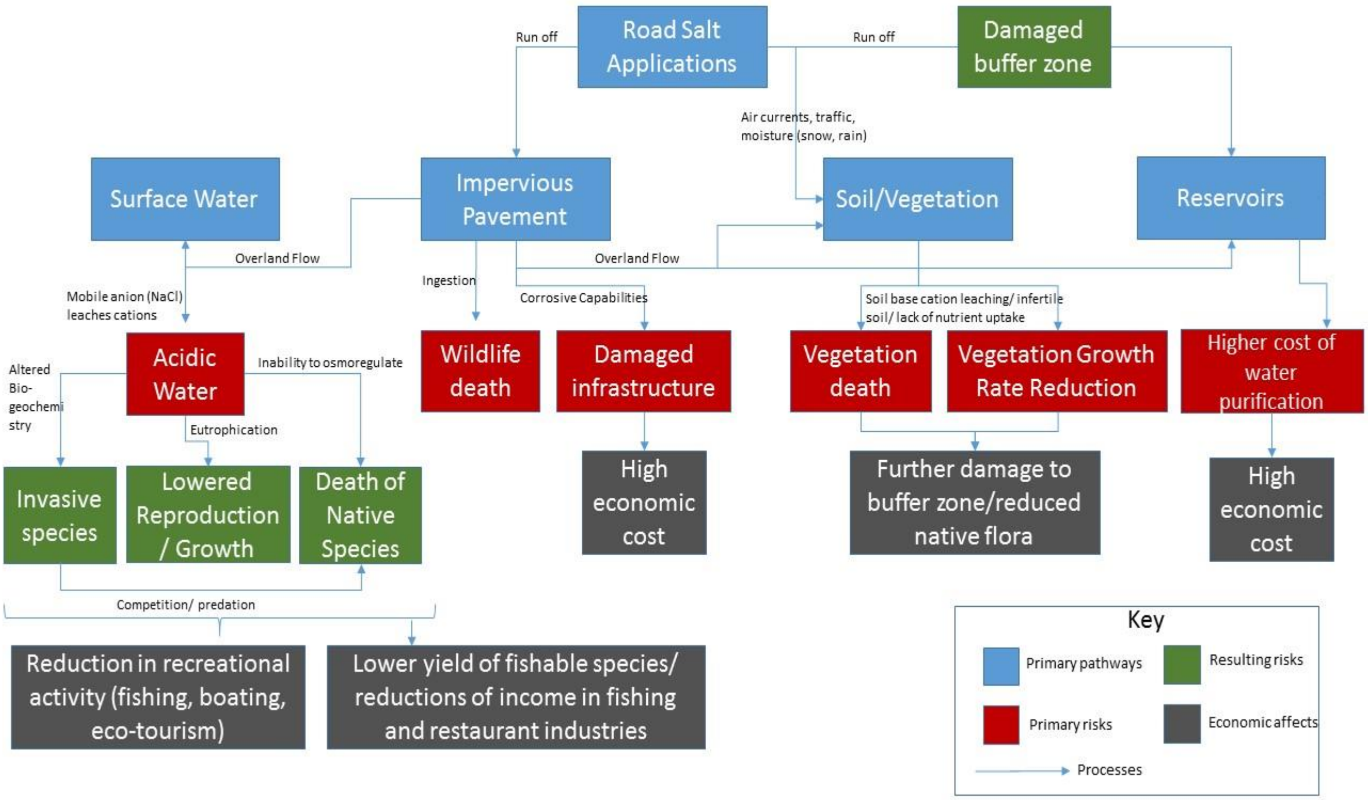
Road salt use is not a one-problem- or one-solution-fits-all situation. Different geographic areas have different needs, ecosystems, funding, priorities, etc. For example, the risks associated with road salt are not as pressing an issue in the southern United States as they are in the mid-Atlantic states. As mentioned previously, the best approach is to look at this problem regionally so that there are fewer data gaps such as region-specific native species, reservoir concentrations, and affected wildlife. The scope of this project is not large enough to cover every parameter pertaining to each location; it will provide a broad understanding such that the correlations are understood and further studies can be conducted.

Dose-response studies included in this report may not be uniform across all locations. As is the case with human biotherapeutics, different individual organisms may experience a range of reactions to identical dosages of a substance. Therefore, the mortality findings presented on plant, bird, and fish species are not to be assumed to be the same in all areas with those same species.

V. Risk Characterization

Figure 5 shows the main risk characterization, summarizing the pathways, risks, and effects of road salt applications. This risk characterization conceptual model encompasses risks to human and ecological health.

Figure 6: Risk Characterization Conceptual Model for Road Salt Applications



Considering the data limitations, there are some conclusions that can be made. The studies provide strong regional findings that imply similar national effects. The studies show that salinity is a major factor liming the natural distribution of plants and animals, that most animal and plant species have a range of tolerance to salinity depending on their osmoregulation, and that soil, when infiltrated by NaCl, changes its chemical make-up, depriving it of its fertility and naturally negative charge. Although there are data gaps in dose-response, many plant and animal species are negatively affected when exposed to higher levels of NaCl. The use of road salt and salt storage is the only process which adds NaCl to the environment.

Abiotic conditions, such as those present when water bodies have above usual concentrations of NaCl, can potentially shift community abundance and diversity. The introduction of invasive species is particularly damaging to native communities. Invasive species generally have a higher range of tolerances, thus allowing them to outcompete native species for resources. When a new and aggressive species is introduced into an ecosystem, it may lack natural predators or controls, allowing it to breed quickly and take over its habitat. Human health and economies are also at risk from invasive species. Many commercial, agricultural, and recreational activities depend on healthy native ecosystems. As these native ecosystems are overtaken by invasive species, the economy is burdened with billions of dollars of related expenses each year such as damages to fisheries, tourism, outdoor recreation, property values, agriculture, and public utility operations. (Invasive Species, NWF).

Damaged ecological health, particularly aquatic health, could cost individuals, companies, and governments billions in lost revenue in addition to putting millions of jobs at risk. The Outdoor Industry Association recently released a report, which determined that outdoor recreation is a large and critical sector of the American economy. Outdoor recreation is responsible for generating 6.1 million direct American jobs, $646 billion in direct consumer spending annually, $39.9 billion in federal tax revenue, and $39.7 billion in state/local tax revenue (Wertz, 2018). Many of these recreational activities are generated from water type activities, and within that sector, the health of the water body is hugely responsible for participation.

Salt contamination can harm the fishing industry in many ways. Increased concentrations of NaCl result in acute to lethal toxicity and reduced reproduction of many fish species. The

Hamilton Project released a report in 2015 with the objective of exploring opportunities for improving the economic prosperity and long-term sustainability of the U.S. fishing industry. Commercial and recreational fishing contributed nearly $90 billion to the U.S. economy in 2013 and over 1.5 million jobs for Americans. Many fisheries are located in saline bay or ocean waters, with other small-scale fisheries being land based. Fresh water fisheries located in areas that receive heavy salting, such as all fishing operations around the Chesapeake Bay Watershed, are heavily influenced by salinity of the water (Johnson, 2008). As the concentrations of NaCl continue to increase, huge hits to fish stocks can be expected. Even salt water fisheries could be impacted as many of the fish spawn in freshwater and eventually make their way to brackish, saline waters (Dews, 2014). While increasing concentrations of NaCl is a more prominent issue for freshwater fishing, NaCl concentrations could eventually impact saltwater fish by going outside the range of their osmoregulation.

IV. Discussion

I. Risk Management Points of Intervention

A risk management outlook always starts with a goal. From our risk assessment, we have identified our goal as lessening the impact of road salt usage on human and ecological health while also preserving human safety in winter weather conditions. More specifically, the goal includes:

1. Reduce human health risks
2. Reduce ecological health risks
3. Reduce economic risks

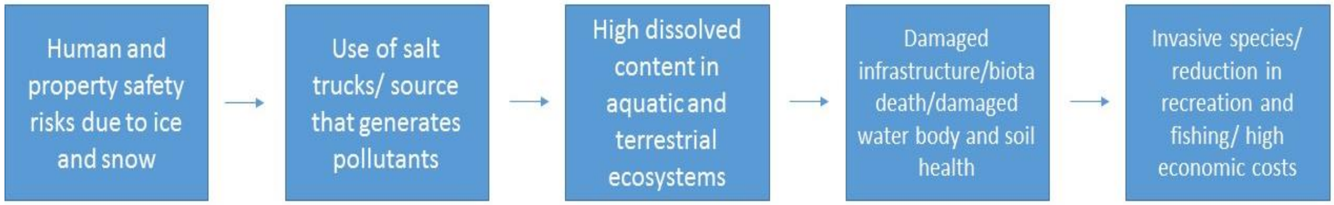
4. Use best efficient available technology
5. Maximize benefit/cost ratio

In this section, we will discuss the available points of intervention. To fully understand all management options, it is important to know all the societal interests and stakeholders involved. Here, an "organization" will mean (1) any public entity that uses or that is responsible for the use of road salt on public roads in the United States or (2) any group that holds ownership or lease to manage a public road. This risk management will not apply to road salts used for domestic or private uses.

The most important stakeholders for this risk management are salt processors and salt miners, highway and department of transportation oversight agencies, the Environmental Protection Agency, and the general public. Risk management is a public policy decision making process and as such, it typically involves competing interests and thus an array of goals and approaches. The risk management process must reflect these different points of view by developing risk management options and analyses as the basis for judging the relative merits of those options.

Figure 6 is an anatomy of risks diagram, typically used in a risk management to explain cause-effect relationships that result in an environmental risk. Between each cause and effect box is a possible, but not always practical, point of intervention. Interventions are actions that break the cause-effect link and thereby mitigate the ultimate effects identified in the anatomy of risks.

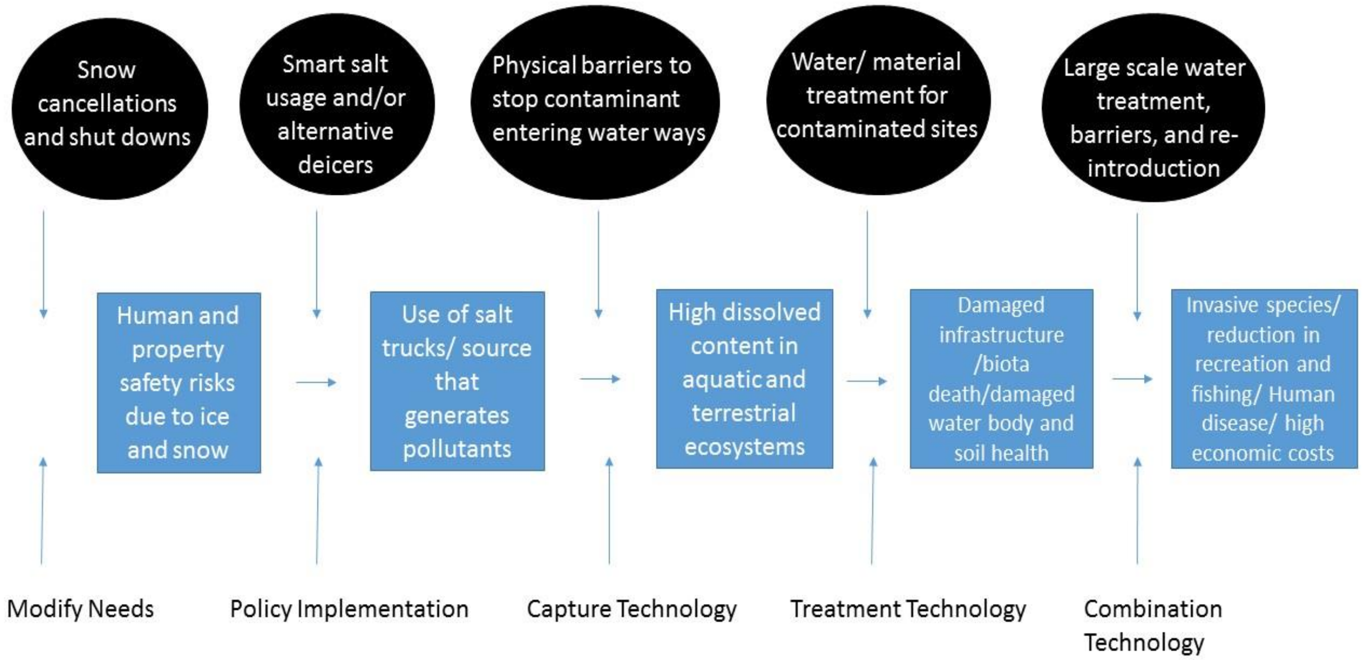
Figure 7: Anatomy of Risks Conceptual Model for Road Salt Use



The initial risk occurs before the application of the contaminant: the dangers associated with ice and snow. These include car accidents, power outages, and threats to human health such as exposure and falling. The second risk arises from the use of NaCl to lessen the risk of the first factor, because state and federal governments believe that fewer injuries and accidents will occur if there is less ice and snow on the road. The next risk occurs when sodium chloride arrives in a large quantity in aquatic and terrestrial ecosystems, altering the chemical makeup of the ecosystem. This leads to damaged infrastructure, biota death, damaged water and soil health, and all other factors reviewed in the risk assessment. The final result is an altered physical, chemical, and biological ecosystem, which as previously discussed, can have huge impacts on human and ecological health in addition to large financial burdens on individuals, organizations, and government.

Figure 7 outlines the possible points of intervention, shown in the circles below, following the anatomy of risks from Figure 6. Each point will be analyzed, and the benefits and disadvantages explored below.

Figure 8: Points of Intervention Conceptual Model for Road Salt Use



I. Point of Intervention: Snow Cancellations and Shut Downs

Typical to risk management is an initial point of intervention that would modify needs by altering policy at a federal, state, or local level. Snow cancellations and shut downs are a point of intervention that require altering policy at those levels. The Mid-Atlantic sits just below the traditional Snowbelt and east of the Appalachian Mountains. The mountains tend to deflect the flow of northern cold air and southern moist air, which makes conditions favorable for ice. Many places in the United States receive massive amounts of snow, such as several midwestern states, yet widespread road salt is not necessary because the need varies by locale. Populations in the Midwest are smaller than those in the Mid-Atlantic and winters are more intense, and so locally people have adapted through the use of snow chains, all wheel or four wheel automobiles, snow mobiles, and better equipped state highway administrations. The mid- to north-Atlantic on the other hand is home to a vast number of government jobs and sizeable cities with larger populations. A regional or state policy that allowed for the dismissal or absence of employees and students without any consequence would limit the need for people to travel as much in dangerous weather conditions and lessen the dependency on road salt. Currently, there are no economic studies indicating how much companies and governments would lose in daily profits during closures. A policy like this would likely exclude private businesses and be enforced only in government organizations and public schools. However, providing incentives to private organizations could promote voluntary participation by these establishments. Additionally, businesses could allow time missed to be made up remotely or throughout a given time frame to limit the impact on profits and employee compensation.

II. Point of Intervention: Smart Salt Usage and Alternative De-icers

The second point of intervention would include policy to promote and regulate smart salt usage and/or alternative deicers. Most de-icing and anti-icing agents used are a mixture of NaCl and anti-caking agents. Other de-icing agents used by state transportation organizations include salt-sand mixtures and magnesium chloride. All of these de-icing compounds pose detrimental effects to asphalt pavement. While their impact on skid resistance is still inconclusive, deicers are known to affect pavement structure and cause loss of strength and elasticity of asphalt concrete. Deicers may also cause corrosion damage to transportation infrastructure such as reinforced or pre-stressed concrete structures and steel bridges (Shi *et al*., 2009). A full analysis of the impacts of these alternative deicers is outside the scope of this report. The purpose of listing alternative deicers is to show the reader that NaCl is not the only compound that can be used.

1. Technological and Mechanical Applications for Smart Salt Use

A study by the Colorado Department of Transportation found many ways to manage the corrosive effects of deicers, such as selection of high-quality concrete, adequate concrete cover and alternative reinforcement, control of deleterious ions or molecules from deicers, injection of beneficial ions or molecules into concrete, and use of non-corrosive deicer alternatives at optimal application rates (Shi, 2009). However, all the suggested management options are costly and require research and development, and all but one entail continuous monitoring and analysis to maintain infrastructural integrity; the lone exception is the use of non-corrosive alternative deicers.

Another study analyzed the alternative deicing method of incorporating a deicing additive into asphalt mixture prior to road construction (Peng *et al*., 2015). The chloride molecules added to the asphalt mixture interact with snow or ice to play a role of self-melting without additional applications of road salt. The study showed that chloride components will gradually migrate from the interior structure of asphalt pavement due to the compression, vibration and wear from traffic load. One downside is that the released chloride anions would still pollute the surrounding environment and construction to some extent.

Non-chemical deicing methods have also been explored. Professor Victor F. Petrenko at Thayer School of Engineering patented four different ice-manipulation methods that use low-voltage electricity to remove ice, prevent it from forming, or either increase or decrease ice-surface friction. For ground surface applications, low voltage electricity is distributed either through a metal grid embedded in the surface or though electrically conductive paint. Ice breaks down through the process of electrolysis, transforming ice directly into hydrogen and oxygen gases (Lamm, 2001). These methods, unlike chemical methods, do not pollute the environment.

Maintenance Decision Support System (MDSS) is a "smart salt" process that involves a computer program targeting location specific forecasts, route data, traffic levels, maintenance materials and practices, reports of weather and road conditions, and previous maintenance actions to make recommendations for future maintenance actions to reduce wasted salt.(NDOR Maintenance Manual, 2010). The MDSS project was a collaboration between groups of diverse stakeholders consisting of state Departments of Transportation (DOT), five national laboratories, and the academic and private sector communities. Recommendations from MDSS are intended to aid maintenance workers in choosing the most effective practice for their specific locations. Information recorded in MDSS is taken from a variety of sources and can be compared to verify data. Temperatures are taken from weather stations or infrared sensors equipped on trucks. The trucks positioning is tracked via Global Positioning System (GPS). A cost-benefit study revealed that the tangible benefits of MDSS significantly outweigh its costs. The study showed that regions in Nebraska that have been using this technology for several years, have seen improved documentation of actual maintenance activities, reduced response and clearance time, reduced labor and equipment costs, reduced corrosion, and reduced environmental impacts (Shi *et al*., 2009).

The Snow and Ice Management Association (SIMA) released a Best Practices for Sustainable Salt Use guideline emphasizing the importance of using calibrated spreaders with automatic controls programed to apply salt at the appropriate time and location, particularly in more risk prone areas such as curves, bridges, overpasses, and shaded roadways. SIMA stated that operator training is just as important to increasing efficiency and minimizing pollution as the actual use of the equipment itself. The Massachusetts DOT has estimated savings close to 10,000 tons of salt in one year by using MDSS and automated salt spreading technology (SIMA, 2017).

2. Alternative Chemical Mixtures for Smart Salt Use

One alternative deicer explored in the Journal of Solid State Chemistry is calcium-magnesium acetate. Acetate-based salts have a similar melting efficiency to that of chloride, and they are less harmful for the surrounding environment; however, they cannot melt snow or ice sustainably on asphalt pavement, because rain or melted snow will wash the acetate anions (Ac^-) away (Miller *et al*., 2018).

An additional alternative is GeoMelt 55, an organic beet juice-based concentrate that can be blended with salt brine to increase ice melting performance. The sticky characteristics of the mixture cause the brine to adhere to the road and leave a longer lasting residue upon the road (Shi *et al*., 2009). In a field study comparing roadway applications of deicers, it appeared that direct sunlight enhanced the performance of beet juice by absorbing solar radiation (Albers, 2015). While using higher concentrations of beet juice will increase de-icing performance, it is recommended not to use more than 20% beet-juice in a mixture to avoid clogging spreaders.

Other deicers that were observed in literature included gravel abrasives used for traction purposes by bonding to the roadway when freezing occurs. Ice Slicer, another product, which contains a mixture of magnesium, chloride, sodium potassium, sulfur, iron, iodine, zinc, copper, phosphorous, and other trace minerals along with natural corrosion inhibitors, can also be used for de-icing. Urea, a natural compound that is very high in nitrogen can be used as a deicer, but when the compound interacts with water, it releases nitrogen and cuts off oxygen supply (Lucas, 2018).

The practice of pre-wetting road salts has also been shown to improve adhesion to pavement surface and reduce the amount of materials wasted when applied to roadways. A field study conducted in Michigan showed 96% retention of pre-wetted salts on road surfaces compared to 70% of the dry salt due to bounce and scatter (Shi *et al*., 2009). Other studies have suggested that pre-wetting accelerates the process of melting ice and snow as well as lowering the effective temperature of the salt.

III. Point of Intervention: Physical Barriers

The third point of intervention involves using physical barriers along heavily salted roads to stop contaminants from entering soils, surface water, and ground water. Physical barriers made of plastic, concrete, sand, nets, or even plants have been used to stop erosion and corrosion, but mainly for coastal erosions from high tides. Certain trees and plants can survive high salt concentrations and act as a physical barrier to prevent widespread distribution of contaminants. There is no conclusive study exploring how much road salt would be taken up by such plants, as this would be dependent on location, plant type, and amount of salt used. It is however reasonable to suggest that this method would only capture a small percentage of NaCl, as it would not prevent NaCl from leeching through cracks in the road into the environment.

IV. Point of Intervention: Water and Material Treatment for Contaminated Sites

The fourth point of intervention will only be available after road salts have entered an ecosystem. This point of intervention would include categorizing tributaries, water bodies, reservoirs, and land (including infrastructure) from least to most important. Individual analysis would be needed to explore what measures, if any, could be taken to treat the damaged ecosystem or property. For example, desalinization is used in developing nations to provide clean drinking water, but it is costly and mostly used for small scale water purification.

There are ways to manage the corrosive effects of deicers, such as by injecting beneficial ions or molecules into metals and concretes to prevent damage to road structures. Additionally, resurfacing and electric cleanings can reverse the damage of NaCl on metal, particularly aluminum (Sereda, 1961). However, these methods are expensive and require continuous maintenance; furthermore, they would likely only a address a small fraction of the damage caused by road salt contamination.

V. Point of Intervention: Combination of Physical Barriers, Water and Material Treatment, and Re-introduction of Species

The final point of intervention would require a combination of large-scale water purification, barriers to stop further contamination, and re-introduction of native species into ecologically significant habitats. Currently no feasible technologies exist that would allow large-scale water desalination without disturbing ecological processes. As previously discussed, barriers are not an effective method of preventing salt contamination due to the widespread pathways the pollutant travels. Re-introduction of native species may work for certain waterways where native species are filter feeders, as they can remove microorganism that cause algal blooms and promote good bacteria that in turn support water body health. This is not a common situation though, and reintroduction often does not work; in fact, sometimes it even increases risks, thereby leading environmental organizations to not recommend it as a method of improving ecological health.

If none of the points of intervention are utilized, there may be some remedial action such as health care for hypertension and accepting fewer ecological services ,and the impacts that would have on the economy, in exchange for road salting.

II. Risk Management Options Matrix

A risk management options matrix is a tool often used in risk assessment and risk management analysis. In Table 6, the matrix enables one to observe points of intervention in a snapshot by identifying all the benefits and disadvantages. It is a conceptual model using the professional judgement of the writer intended both to simplify prioritizing goals and issues and to take action where necessary and effective. Typical parameters of an options matrix include effectiveness at reducing risk, cost of implementation, technical feasibility, and degree of public acceptance.

The efficacy estimations relate to the effect of reduction from that specific operation. The efficacy is the most dependent factor of the measures. The parameters below were used to divide efficacy estimations into three levels.

- High → Prevention measure, potential reduction to very low (non-detectable) levels in watersheds and reservoirs;

- Medium → Reduction measure, reduction to low but detectable levels;
- Low → Limited reduction, additional measures required in series or parallel.

The cost estimate is meant as in indication and is not based on actual cost and experience because those parameters would have to be individually assessed for specific geographic locations in a study. Cost should be read primarily in relation to efficacy and the need of new or additional resources, technology, development, and other resources.

- High → Costs include the need for new technologies and methods, development and testing of those technologies and methods, large work force needs, lobbying, establishment of new economies, or loss of economic activity;
- Medium → Costs include additional research and testing of readily available methods and technologies, some loss of economic activity for small sectors, and lobbying;
- Low → Costs include no additional research and development, no alterations to work force, no change in economic activity, but some costs due to legal action and lobbying.

Technical feasibility relates to costs by means of inputs, processes, output, programs, and procedures. Those options that are more feasible will need less costs for the above parameters. Those options with under developed parameters, will have higher costs.

- High → Current infrastructural designs need to be modified, large engineering and architectural requirements, proposed technology or method has not been tested to work adequately for the appropriate range needed, lack of complete assessment of geo-technical conditions;

- Medium → Some engineering or architectural requirements, and some method testing and modifying for appropriate range needed;
- Low → No engineering or architectural requirements, no methods testing or modifying, some assessment of geo-technical conditions needed.

Degree of public acceptance has perhaps the least parameters out of the other ranks. No public surveys or questionnaires were performed for this analysis because the geographic scope of the risk is too large. People from different regions would likely have very different opinions based off of local needs and resources, so parameters were picked that would likely be consistent.

- High → Risks to human and ecological health reduced, little to no damage to private and public property, no changes to personal income
- Medium → Risks to human and ecological health have minor reductions, damages occur to private or public property, no changes to personal income
- Low → No reductions of risk to human and ecological health, damages occur on a wide scale to private or public property, changes to personal income

Table 6: Risk Management Options Matrix for Road Salt Use

	Snow cancellations and shut downs	Smart salt use and/or alternative deicers	Physical barriers	Water/material treatment	Large scale water treatment, barriers, and reintroduction	Do nothing
Effectiveness at reducing risk	Medium	High	Low	Low	Low	Low
Cost of implementation	High	Medium	High	High	High	Low
Technical feasibility	Low	Medium	High	High	High	Low
Degree of public acceptance	High	High	Low	Low	Low	Low

1. **Snow cancellations and shut downs**
   a. Effectiveness at reducing risks was given a ranking of "medium." If there were fewer risks or detrimental effects associated with missing work, school, and other obligatory requirements, people would not feel the need to travel in dangerous weather conditions, and thus less road salt could be used. However, some de-icing agents would still be necessary for those unable to stay at home and those operating emergency vehicles.
   b. Cost of implementation was given a ranking of "high" due to the monetary losses governments and corporations would suffer by being shut down for weather conditions. This could be partially remedied by allowing those who can to work from home or make up lost hours at another time or day without personal or professional penalty.

c. Technical feasibility was given a ranking of “low” because there would be no required additional technology or equipment necessary to allow people to stay home.

d. Degree of public acceptance was given a ranking of “high” because the general public would likely approve of not having to take the risks of traveling in unsafe weather conditions

2. Smart salt use and alternative deicers

a. Effectiveness at reducing risk was given a ranking of “high.” Through a mix of technological applicators, deicer use would result in highest benefit with less of the contaminant being used. Certain well-studied alternative deicers have less of an impact on ecological settings. Other techniques such as pre-wetting would require even less deicer use.

b. Cost of implementation was given a ranking of “medium.” Much of the costs associated with this point of intervention come from developing methods, technologies, techniques, and training operators. Smart salt use has already been adapted by many states; at this point, it simply needs to be implemented in additional heavy salting states. Costs of implementation would be lower because the effectiveness has already been examined. For certain alternative deicers, costs would include expanding production such as beet additives.

c. Technical feasibility was given a ranking of “medium” for the moderate demands of research and development, operator training, and establishment of procedures and methods.

d. Degree of public acceptance was given a ranking of “high.” The public’s need for de-icing in dangerous weather conditions would be met. Additionally, the public would support lowered risks to infrastructure and property and ecological settings returning to their prior levels of NaCl concentrations, resulting in overall improved ecological health.

3. **Physical barriers**
    a. Effectiveness at reducing risk was given a ranking of "low" due to the large volume of the contaminant still present after implementation. Even with physical barriers, much of the salt would be taken up by plants, waterways, and soil.
    b. Cost of implementation was given a ranking of "high" due to the costs of manpower and equipment necessary to produce and implement physical barriers. To be even partially effective, tens of thousands of miles of physical barriers would need to be installed along the contaminated roadways. The cheapest materials used as physical barriers against erosion are sandbags, which cost anywhere from $28-$43 per cubic yard.
    c. Technical feasibility was given a ranking of "high" due to the potential need for research and development, methods of transportation, and placement of barriers.
    d. Degree of public acceptance was given a ranking of "low." The general public would likely be opposed to the increased traffic and congestion that such a large-scale project would cause. Additionally, the public might oppose the aesthetics, high costs, and lack of efficacy of the barriers.
4. **Water and material treatment**
    a. Effectiveness at reducing risk was given a ranking of "low." The volume of the contaminant present and the bodies of water in question are simply too large for water

treatment. Material treatment is only used for small scale erosion and would not be feasible for abrasions caused by salt on road surfaces.

b. The cost of implementation was given a ranking of “high” because desalinization and material treatment for metals and concrete eroded by salt are extremely costly, vary case by case, and require frequent treatments.

c. Technical feasibility was given a ranking of “high” due to the extensive research that would be required to develop purification systems and material treatment methods for large-scale use.

d. Degree of public acceptance was given a ranking of “low.” People would likely be opposed to tax revenue being spent on large-scale projects that are expensive and ineffective.

5. **Large-scale water treatment, barriers, and re-introduction**

    a. Effectiveness at reducing risk was given a ranking of “low.” The volume of the contaminant and the bodies of water in question are simply too large for water treatment. Material treatment is only used for small scale erosion and barriers will not stop road salt from entering ecosystems through runoff and cracks in otherwise impervious surfaces. Re-introduction is not an effective tool at improving ecological health.

    b. Cost of implementation was given a ranking of “high.” The costs of research and development, production, and implementation needed for a project of this scale would be unrealistic and unattainable.

c. Technical feasibility was given a ranking of “high.” New technologies and methods would need to be created. Cost of production of these technologies for a large-scale operation would be extensive.

d. Degree of public acceptance was given a ranking of “low.” People would likely be opposed to tax revenue being spent on large-scale projects that are expensive and ineffective.

6. Do nothing

a. Effectiveness at reducing risk was given a ranking of “low.” The contaminant would continue to be added into ecological settings at a similar or increased rate. The ecological effects of higher concentrations of sodium chloride in key environmental settings would continue to take place.

b. Cost of implementation was given a ranking of “low.” The costs associated with the impacts that road salt has on the economy, such as impacts on fishing industries, recreation, and tourism, would continue to increase.

c. Technical feasibility was given a ranking of “low.” There would not be a need for additional technology or research to continue producing and dispersing road salt at current rates.

d. Degree of public acceptance was given a ranking of “low.” The economic losses from decreases in recreation, fishing, and seafood industries would result in public disapproval. The erosion of cars, buildings, and roads has high costs and negative risks directly for and to the general public. Ecological well-being and environmental aesthetics are also important to many people.

State and federal policy makers will not adopt policy options unless they can observe its beneficial effects. One study conducted by the Washington State University estimates that the US spends roughly $2.3 billion on road salting, depending on weather conditions that year, but $5 billion to pay for the resulting damages caused by salt, mainly road re-paving (Peng *et al.*, 2015). This huge hit to federal and state budgets may be enough to get policy makers to address the issues with road salt. Smart salt technology and alternative deicers have been shown to work and would be the least costly point of intervention with likely the most benefits. The cost of implementation of methods, technologies, and the increase of cost of alternative deicers, because currently salt is the cheapest chemical deicer on the market, would still be below the staggering $5 billion in estimated damages. The other points of intervention would require large costs in research and development to simply find techniques and methods that may work and then field testing would be needed to fully understand the effectiveness. Snow cancellations would be effective in eliminating the risks to human health regarding accidents, but would likely not gain support from governments and businesses. Roads would still have to be treated for emergency vehicles and mandatory personnel in certain industries.

V. Conclusion

Although data limitations suggest that regional or laboratory based qualitative data cannot be applied for the geographic scope of the risks associated with road salt, it is safe to assume the existence of trends from the data presented in this report. The study conducted by the Worcester Polytechnic Institute found that groundwater sources throughout Massachusetts had anywhere from 51.2% – 74.7% more NaCl than the 250 mg/L limit set by EPA to combat hypertension, cardiac disease, renal disease, and stroke. There are no other processes, natural or man-made, that would result in these high concentrations of NaCl apart from road salting. The study concludes that these findings would likely be observed in groundwater sources of other states that receive heavy salting, mainly the mid to north Atlantic. Homeostasis failure and edema of gizzard are signs of acute toxicity to terrestrial wildlife and were observed at concentrations below the safe limit set by EPA of 1,000 mg/L. When observing salt toxicity in aquatic species, 6 out of the 14 species included in the dose-response analysis showed chronic effects at concentrations below the final acute value of chloride considered safe for aquatic species, set by EPA at 1720 mg/L of chloride. Certain terrestrial and aquatic vegetation observed high sensitivity to chloride concentrations as little as 71 mg Cl^-/L. Other concentrations resulted in impeded growth, reduction of chlorophyll production, reduced reproduction rates, and cellular dehydration. Out of the 16 observed conditions, only in two conditions were there no effects observed. The risk assessment analysis of wildlife, aquatic life, and vegetation implies that one limit concentrations set by federal or state agencies are not a wholesome method at protecting all the biota in an ecosystem and that current salt concentrations in ecosystems pose great risks to biodiversity. The risk characterization for human health risks when using no road salt suggest increased potential for car accidents and slipping incidents in addition to high economic costs associated with increased insurance premiums, and changes to human behavior regarding travelling. To minimize risks to human and ecological life it is necessary to explore alternatives to the standard NaCl approach of road salting.

In the risk management section of the report, points of interventions were picked that would mitigate the risks of road salt that were identified in the risk characterization. These points of intervention included changes to human behavior, technological, mechanical, and chemical innovations, and research and development of new methods. Not all points of intervention were found to be feasible due to effectiveness, cost of implementation, technical feasibility, and/or degree of public acceptance. Regional analysis is critical to determine which solutions would benefit regional needs and to minimize data limitations. Of those points of interventions analyzed, the options matrix suggests that smart salt usage and alternative deicers are the most effective at reducing risks, have the highest cost-benefit ratio, would be technically feasible, and have a high degree of public acceptance as most of the technology and alternatives already exist and have been shown to work.

The use of road salt is a major contributing factor to the long-term salinization of the environment throughout the country. Salinization appears to alter the ecological condition of terrestrial and aquatic ecosystems. Adding salt to the environment has many negative impacts, but the absence of mobility caused by not eliminating salt usage is not practical. Salt corrosion already causes billions of dollars in damage each year to cars, roads, and bridges in addition to all the unknown economic and ecological damages that result from impacted ecosystems. Winter maintenance is a significant portion of state budgets and determining the best practices for winter maintenance is a very comprehensive task. The scope of this project was to give an overview of some of the risks associated with road salts and to present management options to those risks. Many risks such as those to pets, risks of alternative deicers, risk to salt mining industries and employees were not included. Input from academic and government institutions and the public is critical in making effective policy solutions. If road salts continue to be applied to roadways at its current rate, salt concentrations in water bodies, terrestrial ecosystems, and drinking water reservoirs will continue to increase. But, by more aggressively managing and in some cases limiting road salt use through state or federal policy, we may be able to halt, or at least slow, this increase and its impact on our environment and economy.

VI. References

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